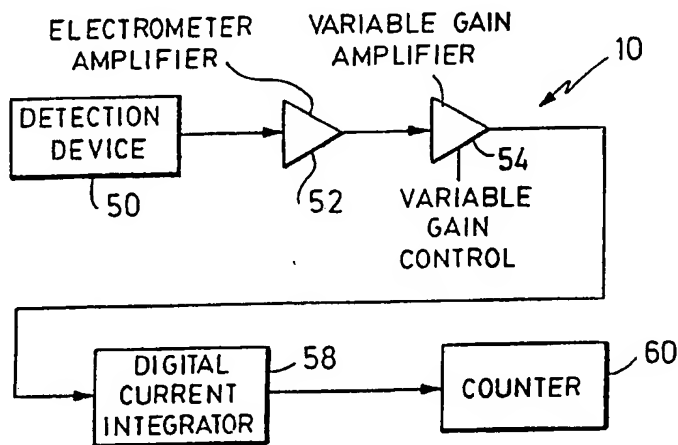




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(54) Title: DIGITAL CHARGE BALANCING CURRENT INTEGRATION IN PENETRATING RADIATION DETECTION SYSTEM



(57) Abstract

An improved circuit for quantifying the energy incident to a detection device in a radiography application is achieved by the present invention. The output of a penetrating radiation detection device is connected to an integrating electrometer amplifier which in turn may be connected to a variable gain amplifier which is connected to a current integrator. The summing node of the current integrator receives current related to the current output from the detection device and receives current of an opposite polarity from a charge dump circuit. An integrating capacitor is also connected to the summing node. A comparator is connected to the output of the integrator and when the output signal of the integrator reaches the comparator's reference level, the comparator triggers the charge dump circuit which places a predetermined charge on the integrating capacitor at the summing node. Because the charge dump supplies a predetermined charge level, the current related to a penetrating radiation incident occurring during the reset period is summed to the charge dump current and no latent period occurs during the reset. A resettable counter counts the number of times the charge dump circuit is triggered and this count per unit of time represents the quantity of energy incident to the detection device.

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10 DIGITAL CHARGE BALANCING CURRENT INTEGRATION
 IN PENETRATING RADIATION DETECTION SYSTEM

15 This invention relates to a method of and an
 apparatus for quantifying the penetrating radiation
 incident to a detection device or set of detection devices
 in a penetrating radiation detection system. In
 particular, the invention relates to an apparatus and
20 method for using digital charge balancing current
 integration techniques to convert the level of energy
 incident on a detection device or set of detection devices
 into corresponding digital pulses which, when measured per
 unit of time, result in a corresponding frequency.

25 In recent years, radiography and radiographics have
 expanded to include methods and apparatus for examining in
 detail the presence, position, size, density, composition,
 and structure of a body, by utilizing penetrating
 radiation principles of tomographic, limited angle
30 tomographic, focal plane tomographic, Compton backscatter
 tomographic, emission tomographic, radiographic, and
 laminographic reconstruction and general principles of
 radiation detection. This definition of radiography and
 radiographics is used throughout this application.
35 Methods and apparatus related to the art are described in
 U.S. Patent Nos. 4,437,006, 4,284,895 and 3,946,234 and
 are incorporated by reference.

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Recent efforts in radiography have been directed toward solving the problem of obscured detail found in conventional penetrating radiation imaging caused by the superimposition of other structural details of the body being examined through which the radiation passes prior to striking a detection device. Efforts have also recently been directed toward problems related to the presence, position, size, density, and composition of a body. As used throughout this application, penetrating radiation includes, but is not limited to, high energy photon, low energy photon, X-ray, gamma ray, alpha particle, beta particle, neutron, other atomic particle, and other subatomic particle radiation, as well as other forms of penetrating and ionizing radiation.

In use, a body or portion of a body is exposed to penetrating radiation along one or more paths. Typically, a detection device is positioned opposite the radiation source. If multiple detection devices are used, a set of detection devices is typically arranged in an array positioned opposite the radiation source. The body to be examined is typically placed between the radiation source and the detection device or set of detection devices. In Compton backscattering, the detection device need not be positioned opposite the radiation source. In emission tomography, the radiation source is contained within the body. Data representative of the radiation absorbed by the body being examined is obtained by examining the radiation striking a detection device or set of detection devices and comparing this detected radiation to the radiation detected when no body is between the radiation source and the detection device or set of detection devices. This latter situation typically occurs in setup and calibration modes.

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The type of detection device used depends on the application and type of penetrating radiation. Detection devices in general convert a portion of the energy of the penetrating radiation striking the detection device into an electrical current. In one type of detection device, including but not limited to a gas ionization chamber or a semiconductor detector, a fraction of the energy of the penetrating radiation striking the detection device is converted directly into a current. In another type of detection device, including but not limited to an organic or inorganic scintillator which may be used in conjunction with a photomultiplier tube or optoelectronic device, the energy of the penetrating radiation initiates a chain of events that ultimately result in an electrical current. Regardless of the detection device used, the amount of current measured is related to the intensity of the penetrating radiation striking the detection device. The current can then be measured by a suitable electric circuit. A detection device or set of detection devices may include, but is not limited to, one of the types of detection devices discussed as examples above.

For example, where a photomultiplier tube is used as a detection device, penetrating radiation strikes the photocathode and progresses through the photomultiplier tube to the anode. The output of the photomultiplier tube appears as current spikes where each spike is related to an incident of energy of the radiation striking the photocathode.

A photomultiplier tube also outputs sporadic current when no energy is incident upon the photocathode. This sporadic current is referred to as dark current and is not to be included in measuring the energy incident upon the photocathode. To measure energy incident upon the photocathode, the output from the anode is connected to a

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pulse amplifier. A threshold noise level is selected and output from the pulse amplifier is examined for peaks exceeding the selected threshold level. Pulses exceeding the threshold are counted. The count, typically measured
5 per unit of time, represents energy incident upon the detection device. (For example, see FIGURE 1(a).)

Because only pulses above the threshold level are counted in a pulse counting scheme, an inaccurate count
10 may result from energy incidents on the photocathode that produce output from the anode below the selected threshold level. Further, exceptionally tall pulses that may result from multiple radiation incidents against the photocathode simultaneously will be counted as a single pulse because
15 the counting criteria is merely to exceed the threshold level regardless of the amount by which the pulse so exceeds. Further, if multiple radiation incidents occur against the photocathode within a brief period of time and if the output pulse from the anode, after processing
20 through the amplifier, does not drop below the threshold level, then the multiple incident strikes will be counted as a single event. This is because typical pulse counting schemes do not discriminate based on the duration of the pulse.

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In a pulse counting scheme, where there is a decay time between the peak of the output pulse and when the output pulse level drops below the threshold level, as shown in FIGURE 1(c), at a sufficiently intense level of
30 energy incident to a photomultiplier, the pulse output from the pulse amplifier will never drop below the threshold level and the pulse counting scheme will fail due to this saturation. (For example, see FIGURE 1(c) illustrating the described conditions.)

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In a traditional integration circuit, output from a detection device charges a capacitor, the charge level is temporarily stored in a sample-and-hold circuit, this value is converted to a digital representation by an analog-to-digital conversion circuit, and the capacitor is reset. Charge from the detection device is not accounted for during the latent period when the capacitor is being read by the sample-and-hold circuit nor when the capacitor is being reset.

A more accurate apparatus and method for measuring the energy incident upon a detection device is achieved by the present invention. A principle advantage of the present invention is the ability to recognize both the height of pulses of electrical current from a detection device as well as the duration of such pulses or series of pulses. Because the present invention utilizes digital charge balancing current integration, the latent period during reset of the integrator is avoided. Further, the relatively low saturation level associated with pulse counting is also avoided. The invention results in a more accurate and wider dynamic range measurement of energy incident upon the detection device. Additionally, the invention provides a direct digital output related to the radiation striking the detection device without the use of sample-and-hold circuitry or analog to digital conversion circuitry. This eliminates error introduced by noise or bias associated with the sample-and-hold and analog-to-digital circuits. The invention further avoids the error introduced in quantifying an analog output into a discrete number of bits in an analog-to-digital conversion.

Broadly speaking, the circuit of the invention for quantifying the energy incident upon a detection device from a penetrating radiation source in a radiography application comprises an integrating electrometer

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amplifier connected to the output of the detection device. The output of the electrometer amplifier is in turn connected to the input of a current integrator via an optional externally controllable variable gain amplifier. 5 If the optional variable gain amplifier is utilized, the current integrator is connected to the output of the variable gain amplifier at the summing node of the current integrator. If the variable gain amplifier is not used, the current integrator is connected to the output of the 10 electrometer amplifier at the summing node of the current integrator.

A comparator compares the output of the current integrator to a reference voltage and resets the 15 integrator when the output of the integrator approximately equals the reference voltage. The output of the comparator is connected to a resettable counter which enables the user to determine the energy incident to the detection device by counting the number of times the 20 integrator is reset. This count, measured per unit of time, is the frequency of the energy incident on the detection device.

Preferably, the integrator contains an integrating 25 capacitor connected between the summing node and the output of the integrator. The capacitor is configured with the polarity of the signal from the electrometer amplifier or variable gain amplifier opposite the polarity of the capacitor at the summing node. The capacitor is 30 charged from a charge dump circuit and the charge dump circuit is triggered by the comparator output. The trigger for the charge dump circuit comprises a one shot timer having a predetermined period. When the input signal to the comparator approximately equals the 35 reference voltage to the comparator, the comparator triggers the one shot timer which connects a source of

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electric charge to the summing node for the period of the one shot timer. At the end of this period, the one shot timer disconnects the source of electric charge from the summing node. This places a predetermined amount of charge on the integrating capacitor.

Because the polarity of the capacitor is opposite that of the output signal from the electrometer amplifier and the variable gain amplifier at the summing node, there is no latent period during reset. Therefore, any current introduced at the summing node by the electrometer amplifier or variable gain amplifier will still be measured by the circuit. This is the charge balancing of the integrator. The full scale frequency of the circuit is a function of the period of the one shot timer. The full scale frequency represents the maximum current that can be measured by the invention.

When at least two detection devices are in use, the circuit summarized above is repeated for each detection device. Typically, where multiple detection devices are used, the variable gain control is connected to a normalization controller. The normalization controller provides for the measuring, comparing and adjusting of the gain associated with each variable gain amplifier and for the normalizing of the outputs of the variable gain amplifiers. The normalization controller is typically active only during setup and calibration modes.

Broadly speaking, the method of the present invention for quantifying the energy incident to a detection device in a radiography application includes the steps of striking a detection device with incidents of penetrating radiation. In a preferred embodiment, the detection device produces an output current related to the intensity

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of the radiation striking the detection device. The output of the detection device is integrated and can also be amplified to produce a first voltage. This first voltage may be amplified in a variable gain amplifier.

5 The variable gain control for the variable gain amplifier is externally connectable. If the variable gain amplifier is used, the resulting amplified voltage level is converted to an input current proportional to the first voltage and this input current is connected to the summing

10 node of an integrator. If the variable gain amplifier is not used, the first voltage is converted to an input current proportional to the first voltage. This input current is connected to the summing node of an integrator. This current is integrated through an integrator

15 preferably having an integrating capacitor connected between the summing node and the output of the integrator. The polarity of the integrator input current is opposite the polarity of the integrating capacitor at the summing node. The output from the integrator is then compared to

20 a reference voltage and a predetermined charge is dumped into the integrating capacitor when the output from the integrator approximately equals the reference voltage. When the charge is dumped to the integrating capacitor, the integrator is reset and no latent period occurs during

25 reset.

Charge is preferably dumped to the integrating capacitor thus resetting the integrator through the use of a one shot timer triggered by the comparator. The timer

30 has a predetermined period and the timer is connected to a source of electric charge. When triggered, the timer connects the source of electric charge to the summing node for the period of the one shot timer. The full scale frequency of the circuit is a function of the period of

35 the one shot timer.

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The number of times the integrator is reset is counted and this number represents the amount of energy incident to the detection device.

5 In another method of the present invention, at least two detection devices are used. The method described above is repeated for each detection device. However, the variable gain control associated to each variable gain amplifier is connected to a normalization controller. The
10 normalization controller measures, compares and adjusts the gain associated with each variable gain amplifier and normalizes the outputs of the variable gain amplifiers. Normalization typically occurs only during setup and calibration modes.

15 In the invention, quantization error is fixed at one minimum charge unit regardless of the total charge measured. A minimum charge unit is the charge supplied by the charge dump circuit during a reset. The minimum
20 charge unit can be chosen sufficiently small relative to the total charge to be measured to assure a desired minimum level of error.

25 FIGURE 1(a), (b) and (c) illustrate output signals of a detection device.

FIGURE 2 is a block diagram of a first preferred embodiment of the invention.

30 FIGURE 3 is a schematic diagram of a first preferred embodiment of the invention.

FIGURE 4 is a schematic diagram of a second preferred embodiment of the invention.

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FIGURE 5(a) and (c) illustrate electrical current related to output from the electrometer amplifier of the invention.

5 FIGURES 5(b) and (d) illustrate charge on the integrating capacitor of the invention.

FIGURES 2 and 3 illustrate a first preferred embodiment of quantifying circuit 10 in accordance with the present invention. The present invention relates to an improvement in quantifying energy incident to a detection device in a radiography application. In particular, quantifying circuit 10 of the invention utilizes digital charge balancing current integration techniques in place of pulse counting or simple integration techniques utilizing sample-and-hold and analog-to-digital conversion circuits.

20 In the first preferred embodiment, penetrating radiation detection device 50 is used to determine incident radiation. The output of detection device 50 is illustrated in FIGURE 1.

25 Where a photomultiplier tube is used as detection device 50, an ideal photomultiplier tube would have zero output when not exposed to the energy from penetrating radiation and would create a short duration current pulse for each incident of penetrating radiation striking the photomultiplier. FIGURES 1(a), (b) and (c) illustrate the output from a detection device, such as a photomultiplier tube for two incidents. The threshold level is chosen to overcome the dark current of the photomultiplier.

35 FIGURE 1(a) shows two incidents significantly separated in time such that the peak related to the first incident drops below the threshold level prior to the

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beginning of the second incident. FIGURE 1(b) illustrates two incidents occurring closer in time than those incidents illustrated in FIGURE 1(a). In particular, the second incident begins at time 2 while the decay from the first incident does not finish until after time 3. Significantly, the pulse from the first incident drops below the threshold level prior to the pulse from the second incident rising above the threshold level. In integrating the area under the curve, that is, measuring the instantaneous current from the detection device, the present invention recognizes both incidents. In both FIGURES 1(a) and (b), a pulse counter would recognize two incidents.

The present invention integrates the area under the curves illustrated by the two incidents in FIGURE 1(c). In FIGURE 1(c), the decay from the first incident does not drop below the threshold before the current from the second incident rises above the threshold. In a pulse counting scheme, the two incidents illustrated in FIGURE 1(c) would be treated as a single incident. In a simple integration circuit, the second incident may not be accounted for if it occurs during reset period while the integrator is in a latent period.

The type of detection device chosen for detection device 50 depends on the application and type of penetrating radiation. Detection devices in general convert a portion of the energy of the penetrating radiation striking the detection device into an electrical current. For example, in one type of detection device, including but not limited to a gas ionization chamber or semiconductor detector, a fraction of the energy of the penetrating radiation striking the detection device is converted directly into a current. In another type of detection device, including but not limited to an organic

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or inorganic scintillator which may be used in conjunction with a photomultiplier tube or optoelectronic device, the energy of the penetrating radiation initiates a chain of events that ultimately result in an electrical current.

5 Regardless of the detection device used, the amount of current measured is related to the intensity of the penetrating radiation striking the detection device. The above list of example detection devices is only a partial list of possible devices for the detection of penetrating

10 radiation. Other detection devices are known to those skilled in the art. This list is, therefore, not a limitation of the present invention.

FIGURE 2 illustrates, in block diagram, a first preferred embodiment of quantifying circuit 10 of the

15 present invention. The output of detection device 50 is connected to the input of electrometer amplifier 52. The output of electrometer amplifier 52 is connected to variable gain amplifier 54. The gain of variable gain

20 amplifier 54 is controlled by variable gain control 56. The output of variable gain amplifier 54 is input to digital current integrator 58. The output of digital current integrator 58 connects to resettable counter 60.

25 FIGURE 3 shows a schematic diagram of the first preferred embodiment of the invention. Detection device 50 is connected to the inverting input of electrometer operational amplifier 108 through electrometer amplifier input resistor 100.

30 The non-inverting input of electrometer operational amplifier 108 is connected to system ground 102. Electrometer operational amplifier 108 serves as an integrating amplifier. Capacitor 106 and feedback

35 resistor 104 are connected in parallel and are connected between the output of electrometer operational amplifier

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108 and the inverting input of electrometer operational amplifier 108.

5 The output of electrometer operational amplifier 108 is also connected to variable gain amplifier input resistor 110. The output from resistor 110 is connected to both the inverting input of variable gain operational amplifier 114 and variable resistance 112. The non-inverting input of variable gain operational amplifier 114
10 is connected to system ground. The output of variable gain operational amplifier 114 is fed back to the inverting input of variable gain operational amplifier 114 through variable resistance 112. Variable resistance 112 is controlled by variable gain control 56. Variable
15 resistance 112 is shown in phantom to indicate that variable resistance 112 may take the form of a simple potentiometer or a more complex network externally controllable by signals generated external to the circuit by an electronic controller or by another signal capable
20 of varying the gain of variable gain operational amplifier 114.

 The output of variable gain operational amplifier 114 is also connected to integrator input resistor 116. The
25 output from integrator input resistor 116 is connected to the non-inverting input of integrator operational amplifier 124 and is also connected to one side of integrator filter capacitor 118. The other side of integrator filter capacitor 118 is connected to system
30 ground. Integrator standoff resistor 120 has one side connected to system ground and has its other side connected to the inverting input of integrator operational amplifier 124. The inverting input of integrator operational amplifier 124 is also referred to as the
35 summing node. Integrating capacitor 122 is connected

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between the summing node and the output of integrator operational amplifier 124.

5 The output of integrator operational amplifier 124 is connected to the inverting input of comparator operational amplifier 126. The non-inverting input of comparator operational amplifier 126 is connected to a reference voltage which, in all preferred embodiments, is -0.6 volts. The output of comparator operational amplifier 126
10 is connected to the trigger of one shot timer 130. The period of one shot timer 130 is set by the value of timing capacitor 128 which is connected between one shot timer 130 and system ground 102. When triggered, one shot timer 130 connects current source 132 to summing node 134 by
15 switching electronic switch 136. When not triggered, electronic switch 136 connects current source 132 to the output of integrator operational amplifier 124. The polarity of current source 132 is opposite that of the current through integrator standoff resistor 120.

20 Resettable counter 60 is connected to the output of one shot timer 130 and counts the number of times one shot timer 130 is triggered. Counter 60 may be a simple counter or a more expansive system capable of accounting
25 for the number of times one shot timer 130 is triggered.

 In use, as shown in FIGURE 2, penetrating radiation incident on detection device 50 cause electrical current, typically in the form of current pulses to be produced as
30 output from detection device 50. Electrometer amplifier 52 serves as both an integrator and an amplifier and produces a voltage level proportional to the current value output from detection device 50. The output from
 electrometer amplifier 52 is amplified through variable
35 gain amplifier 54. Because the output levels associated with different detection devices can differ significantly,

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variable gain control 56 allows the circuit of the present invention to compensate for different detection devices. The output of variable gain amplifier 54 is a voltage which passes through a resistor resulting in a determinable current as input to digital current integrator 58. Digital current integrator 58 solves for the area under the current curve as illustrated in FIGURES 1(a), (b) and (c).

10 Digital current integrator 58 of FIGURE 2 contains a current integrator, a comparator and a charge dump circuit. The output from the current integrator serves as input to a comparator and the comparator triggers the charge dump circuit when the current integrator output is approximately equal to a reference voltage at the
15 comparator. The charge dump circuit serves to recharge the integrator when the comparator triggers the charge dump circuit. Counter 60 counts the number of times the charge dump circuit is triggered causing the integrator to
20 be reset.

FIGURES 3 and 5 allow a more detailed examination of quantifying circuit 10. In operation, penetrating radiation incident on detection device 50 creates
25 electrical current typically in the form of a current pulse. This current pulse is integrated and amplified through electrometer operational amplifier 108 resulting in a voltage level proportional to the current value input to electrometer operational amplifier 108. This voltage
30 level is amplified through variable gain operational amplifier 114 and passed through integrator input resistor 116 producing a positive current through standoff resistor 120 at the summing node. Three such currents are shown in FIGURE 5(a). Integrating capacitor 122, when fully
35 charged, has a polarity opposite that of the current from variable gain operational amplifier 114. Therefore, the

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current from variable gain operational amplifier 114 discharges integrating capacitor 122.

5 As shown in FIGURE 5(b), integrating capacitor 122 is fully charged at time 1. Looking also at FIGURE 5(a), a first penetrating radiation incident can be seen at time 2. This first incident causes integrating capacitor 122 to discharge by an amount related to the penetrating radiation incident on detection device 50 at time 2. The
10 discharge is repeated for the incident at time 4.

The incident at time 12 causes the voltage output of integrator operational amplifier 114 to fall below the reference level of comparator 126, triggering one shot
15 timer 130 and fully recharging integrating capacitor by time 15.

The output of integrator operational amplifier 114 is a negative sloping ramp whose slope is related to the
20 current input to the summing node. This output is compared by comparator operational amplifier 126 to the reference level and when the output value of integrator operational amplifier 124 approximately equals the reference level, comparator operational amplifier 126
25 triggers one shot timer 130. One shot timer 130 connects current source 132 to the summing node for a predetermined period of time. The period is determined by the value selected for timing capacitor 128. The full scale frequency of quantifying circuit 10 is a function of the
30 period one shot timer 130. The full scale frequency represents the maximum current that can be measured by quantifying circuit 10.

When one shot timer 130 is triggered, integrating
35 capacitor 122 is reset. Reset consists of connecting the current source to the summing node for a period of time

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equal to the period of one shot timer 130. The present invention results in no latent period during reset. For example, if there were no further incidents on detection device 50 during the time one shot timer 130 is triggered, then no additional current would pass through integrator standoff resistor 120 and current source 132 would simply be connected to summing node 134 and recharge integrating capacitor 122 in a polarity opposite that of the current previously passed through integrator standoff resistor 120. Because current source 132 is a constant current source and because the period of one shot timer 130 is predetermined, a known amount of charge will be placed on integrating capacitor 122 when one shot timer 130 is triggered.

FIGURES 5(c) and (d) reflect the same series of three incidents as shown in FIGURES 5(a) and (b) and add a fourth incident at time 14, during the reset of the integrator and recharge of integrating capacitor 122. Because of the opposite polarities of the current through integrator standoff resistor 120 and that supplied by current source 132 there will simply be a lesser charge existing at summing node 134 at the end of the period of one shot timer 130, as shown in FIGURE 5(d) at time 15. The comparator will continue to check for the same reference voltage level prior to next triggering one shot timer 130. The incident during reset merely results in a lower charge at summing node 134 at the end of the reset period than would have existed had no incident occurred. The charge at summing node 134 at the end of the reset period is thus reduced by the amount of charge resulting from the incident that occurred during the reset period. This is the charge balancing of the integrator. Therefore, it is immaterial to integrating capacitor 122 and integrator operational amplifier 124 whether the incident occurs during or after reset because the net

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charge on integrating capacitor 122 will be the same due to current source 132 having a polarity opposite that of the current through integrator standoff resistor 120 and due to current source 132 being connected to summing node 134 for a predetermined time period.

In the method of the first preferred embodiment of quantifying the energy incident to a detection device in a radiography application, penetrating radiation detection device 50, which produces an electrical current when penetrating radiation is incident upon it, is connected to an integrator that is able to serve as an integrating amplifier such as electrometer operational amplifier 108. Output from integrating amplifier 108 is amplified in the preferred embodiment by variable gain amplifier 114. The variable gain can be controlled through variable gain control 56. Variable gain control 56 is externally controllable in the first preferred embodiment. The amplified voltage passes through integrator input resistor 116 in the preferred embodiment producing an input current through integrator standoff resistor 120 connected to summing node 134 of integrator operational amplifier 124.

In the method of the preferred embodiment, integrating capacitor 122 has a negative charge at the summing node and the output from the variable gain amplifier current is positive at the summing node. Current resulting from penetrating radiation incident on detection device 50 serves to discharge the negatively charged integrating capacitor 122 and when the negatively sloping output voltage from integrator operational amplifier 124 is approximately equal to a reference voltage, one count is recorded and integrating capacitor 122 is recharged. In the method of the preferred embodiment the output of integrator operational amplifier 124 is input to comparator operational amplifier 126 and

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comparator operational amplifier 126 triggers one shot timer 130 when the negatively sloping output voltage from integrator operational amplifier 124 approximately equals the reference voltage input to comparator operational amplifier 126 of -0.6 volts.

In the method of the preferred embodiment, constant current source 132 supplies a negative current for a predetermined period of time to summing node 134. One shot timer 130 controls electronic switch 136 and connects current source 132 to summing node 134 for the period of time fixed by the value of timing capacitor 128. In the preferred method, the number of times integrating capacitor 122 is reset is counted by resettable counter 60. This count per period of time represents the number of penetrating radiation incidents occurring in detection device 50.

In all preferred embodiments, there is no latent period during reset because the opposite polarities at the summing node of current source 132 and the current related to penetrating radiation incidents on the detection device allow the capacitor to account for incidents occurring during reset. This is the charge balancing of the integrator.

FIGURE 4 illustrates a second preferred embodiment of the present invention involving at least two detection devices. Each detection device comprises a circuit similar to that described for the first preferred embodiment. However, variable gain control 256 and variable gain control 356 are connected to normalization controller 400. Normalization controller 400 measures and compares the outputs of electrometer amplifiers 208 and 308 and variable gain amplifiers 214 and 314, and adjusts variable gain controls 256 and 356 respectively to

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normalize the outputs of variable gain amplifiers 214 and 314 respectively. Normalization controller 400 typically adjusts variable gain controls 256 and 356 during setup and calibration modes where normalization is appropriate to establish levels prior to inserting a body between the radiation source and the detection devices.

In the method of the second preferred embodiment, at least two detection devices are present and each detection device has a related electrometer amplifier, variable gain amplifier, integrator, and reset circuit.

As shown in FIGURE 4, in the method of the second preferred embodiment, variable gain controls 256 and 356 are controlled by normalization controller 400. Normalization controller 400 measures and compares voltages from electrometer operational amplifier 208 and 308 and, adjusts each associated variable gain controller 256 and 356 to normalize output voltages from variable gain operational amplifiers 214 and 314.

In the method of the second preferred embodiment, normalization controller 400 is active during setup and calibration modes where normalization is appropriate to establish levels prior to inserting a body between the radiation source and the detection devices.

The charge balancing current integration of the present invention avoids problems with latent periods during reset as in other current integration schemes and is able to recognize multiple penetrating radiation incidents occurring simultaneously due to the integrator's production of a voltage level proportional to the current, as opposed to merely counting pulses above a threshold level. Unlike pulse counting, the present invention has

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no inherent limitation as to the frequency of incidents that can be counted.

Further modifications and alternative embodiments of the apparatus and method of this invention will be apparent to those skilled in the art in view of this description. Accordingly, this description is to be construed as illustrative only and is for the purpose of teaching those skilled in the art the manner of carrying out the invention. It is to be understood that the forms of the invention herein shown and described are to be taken as the presently preferred embodiments. For example, equivalent elements may be substituted for those illustrated and described herein, and certain features of the invention may be utilized independently of the use of other features, all as would be apparent to one skilled in the art after having the benefit of this description of the invention.

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CLAIMS:

1. A circuit for quantifying the energy incident to a detection device in a radiography application comprising:

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a detection device having an output of electrical current related to penetrating radiation incident to said detection device;

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an integrating electrometer amplifier having an input and an output and said electrometer input being connected to said detection device;

15

a variable gain amplifier having a signal input, a signal output and a control input, said electrometer amplifier output being connected to said variable gain amplifier input and said variable gain amplifier control input being externally connectable;

20

a current integrator having a signal input, a summing node, and a signal output and said integrator signal input being connected to said variable gain amplifier output;

25

a comparator having a signal input, a reference voltage input and an output, said comparator input being connected to said current integrator output, and said comparator reference voltage input being connected to a reference voltage; and,

30

a charge dump circuit having an input, an output and a trigger, said charge dump trigger being connected to said comparator output, said charge dump input being connected to a source of

35

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electric charge, and said charge dump output being connected to said summing node, said charge dump being triggered to supply a predetermined charge from said charge dump output on each triggering output from said comparator, resetting said current integrator and having no latent period during reset of said integrator.

10

2. The circuit of claim 1 wherein said integrator further comprises a capacitor, said capacitor being connected between said summing node and said integrator output.

15

3. The circuit of claim 2 wherein said charge dump trigger further comprises a one shot timer having a predetermined period, when triggered said one shot timer connects said source of electric charge to said summing node in a polarity opposite the polarity of said variable gain amplifier signal output, and at the end of said period said one shot timer disconnects said source of electric charge from said summing node.

25

4. The circuit of claim 1 further comprising a resettable counter having an input connected to said comparator output.

30

5. The circuit of claim 1 wherein said detection device is a photomultiplier tube.

35

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6. A circuit for quantifying the energy incident to a detection device in a radiography application comprising:

5 a detection device having an output of electric current related to penetrating radiation incident to said detection device;

10 an integrating electrometer amplifier having an input and an output and said electrometer input being connected to said detection device;

15 a current integrator having a signal input, a summing node and a signal output and said integrator signal input being connected to said electrometer amplifier output;

20 a comparator having a signal input, a reference voltage input and an output, said comparator input being connected to said current integrator output, and said comparator reference voltage input being connected to a reference voltage; and,

25 a charge dump circuit having an input, an output and a trigger, said charge dump trigger being connected to said comparator output, said charge dump input being connected to a source of electric charge, and said charge dump output being connected to said summing node, said
30 charge dump being triggered to supply a predetermined charge from said charge dump output on each triggering output from said comparator, resetting said current integrator and having no latent period during reset of said
35 integrator.

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7. The circuit of claim 6 wherein said integrator further comprises a capacitor, said capacitor being connected between said summing node and said integrator output.

8. The circuit of claim 7 wherein said charge dump trigger further comprises a one shot timer having a predetermined period, when triggered said one shot timer connects said source of electric charge to said summing node in a polarity opposite the polarity of said electrometer amplifier output, and at the end of said period said one shot timer disconnects said source of electric charge from said summing node.

9. The circuit of claim 6 further comprising a resettable counter having an input connected to said comparator output.

10. The circuit of claim 6 wherein said detection device is a photomultiplier tube.

11. A radiographic apparatus comprising:

a penetrating radiation source;

a detection device having an output of electrical current related to penetrating radiation incident to said detection device;

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an integrating electrometer amplifier having an input and an output and said electrometer input being connected to said detection device;

5 a current integrator having a signal input, a summing node and a signal output and said integrator signal input being connected to said electrometer amplifier output;

10 a comparator having a signal input, a reference voltage input and an output, said comparator input being connected to said current integrator output, and said comparator reference voltage input being connected to a reference voltage;
15 and,

a charge dump circuit having an input, an output and a trigger, said charge dump trigger being connected to said comparator output, said charge
20 dump input being connected to a source of electric charge, and said charge dump output being connected to said summing node, said charge dump being triggered to supply a predetermined charge from said charge dump
25 output on each triggering output from said comparator, resetting said current integrator and having no latent period during reset of said integrator.

30

12. A circuit for quantifying the energy incident to detection devices in a radiography application comprising:

at least two detection devices each having an output
35 of electrical current related to penetrating

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radiation incident to each individual said
detection device;

an integrating electrometer amplifier exclusively
associated to each detection device, each said
electrometer amplifier having an input and an
output, and each said electrometer input being
exclusively connected to its associated said
detection device;

a variable gain amplifier exclusively associated to
each electrometer amplifier, each said variable
gain amplifier having a signal input, a signal
output and a gain control input, each said
electrometer amplifier output being exclusively
connected to its associated said variable gain
amplifier input, and each said variable gain
amplifier gain control input being connected to
a normalization controller;

a current integrator exclusively associated to each
variable gain amplifier, each said current
integrator having a signal input, a summing node
and a signal output, and each said integrator
signal input being exclusively connected to its
associated said variable gain amplifier output;

a comparator exclusively associated to each
integrator, each said comparator having a signal
input, a reference voltage input and an output,
each said comparator input being exclusively
connected to its associated said current
integrator output, and each said comparator
reference voltage input being connected to an
external reference voltage; and,

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5 a charge dump circuit exclusively associated to each
comparator, each said charge dump circuit having
an input, an output and a trigger, each said
charge dump trigger being exclusively connected
to its associated said comparator output, each
said charge dump input being connected to a
source of electric charge, and each said charge
dump output being exclusively connected to its
associated said summing node, each said charge
10 dump being individually triggered to supply a
predetermined charge from said charge dump
output on each pulse from its associated said
comparator output, resetting its associated said
current integrator and having no latent period
15 during reset of said integrator.

13. The circuit of claim 12 wherein each of said
integrators further comprise a capacitor, said capacitor
20 being connected between its associated said summing node
and its associated said integrator output.

14. The circuit of claim 13 wherein each of said charge
25 dump triggers further comprise a one shot timer having a
predetermined period, when triggered each of said one shot
timers connect said source of electric charge to its
associated said summing node in a polarity opposite the
polarity of its associated said variable gain amplifier
30 signal output, and at the end of said period said one shot
timer disconnects said source of electric charge from said
summing node.

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15. The circuit of claim 12 further comprising resettable counters having inputs exclusively associated to each of said comparator outputs.

5

16. The circuit of claim 12 wherein each of said detection devices is a photomultiplier tube.

10

17. The circuit of claim 12 wherein said normalization controller comprises means for measuring and comparing each associated said variable gain amplifier and adjusting each of said variable gain control inputs and normalizing said variable gain amplifier outputs.

15

18. A radiographic apparatus comprising:

a penetrating radiation source;

20

at least two detection devices each having an output of electrical current related to penetrating radiation incident to each individual said detection device;

25

an integrating electrometer amplifier exclusively associated to each detection device, each said electrometer amplifier having an input and an output, and each said electrometer input being exclusively connected to its associated said detection device;

30

a variable gain amplifier exclusively associated to each electrometer amplifier, each said variable gain amplifier having a signal input, a signal output and a gain control input, each said

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5 electrometer amplifier output being exclusively
connected to its associated said variable gain
amplifier input, and each said variable gain
amplifier gain control input being connected to
a normalization controller;

10 a current integrator exclusively associated to each
variable gain amplifier, each said current
integrator having a signal input, a summing node
and a signal output, and each said integrator
signal input being exclusively connected to its
associated said variable gain amplifier output;

15 a comparator exclusively associated to each
integrator, each said comparator having a signal
input, a reference voltage input and an output,
each said comparator input being exclusively
connected to its associated said current
20 integrator output, and each said comparator
reference voltage input being connected to an
external reference voltage; and,

25 a charge dump circuit exclusively associated to each
comparator, each said charge dump circuit having
an input, an output and a trigger, each said
charge dump trigger being exclusively connected
to its associated said comparator output, each
said charge dump input being connected to a
source of electric charge, and each said charge
30 dump output being exclusively connected to its
associated said summing node, each said charge
dump being individually triggered to supply a
predetermined charge from said charge dump
output on each pulse from its associated said
35 comparator output, resetting its associated said

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current integrator and having no latent period during reset of said integrator.

5 19. A radiographic apparatus comprising:

source means to supply penetrating radiation;

10 detection means for supplying electrical current
related to said penetrating radiation incident
to said detection means;

15 an integrator to integrate said electrical current
from said detection means to produce an
integrated output;

a comparator to compare said integrated output to a
reference level;

20 resetting means to reset said integrator when said
integrated output approximately equals said
reference level and said resetting means
produces no latent period in said integrator;
and,

25 counting means to account for the number of resets of
said integrator.

30 20. A method of quantifying the energy incident to a
detection device in a radiography application comprising:

35 striking a detection device with penetrating
radiation producing output electrical current
from said detection device and said output
electrical current is related to said

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penetrating radiation incident on said detection device;

5 integrating said detection device output electrical current, and producing a first voltage;

10 amplifying said first voltage in a variable gain amplifier; having an externally connectable variable gain control and producing an amplified voltage level;

15 generating an integrator input current proportional to said amplified voltage and connecting said integrator input current to a summing node;

20 integrating said integrator input current through an integrator having an input connected to said summing node, a capacitor connected between said summing node and the output of said integrator, and the polarity of said integrator input current being opposite the polarity of said capacitor at said summing node;

25 comparing said output from said integrator to a reference voltage and dumping charge into said capacitor when said output from said integrator approximately equals said reference voltage, resetting said integrator and having no latent period during reset of said integrator.

30

35 21. The method of claim 20 wherein said step of dumping charge into said capacitor and resetting said integrator comprises triggering a one shot timer, said timer having a predetermined period, said one shot timer being connected to a source of electric charge, and said triggered one

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shot connects said source of electric charge to said summing node for said period.

5 22. The method of claim 20 further comprising counting the number of said resets of said integrator.

10 23. A method of quantifying the energy incident to a detection device in a radiography application comprising:

striking a detection device with penetration
radiation producing output electrical current
from said detection device and said output
15 electrical current is related to said
penetrating radiation incident on said detection
device;

20 integrating said detection device output electrical
current, and producing a first voltage;

generating an integrator input current proportional
to said first voltage and connecting said
integrator input current to a summing node;

25 integrating said integrator input current through an
integrator having an input connected to said
summing node, a capacitor connected between said
summing node and the output of said integrator,
30 and the polarity of said integrator input
current being opposite the polarity of said
capacitor at said summing node;

35 comparing said output from said integrator to a
reference voltage and dumping charge into said
capacitor when said output from said integrator

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approximately equals said reference voltage,
resetting said integrator and having no latent
period during reset of said integrator.

5 24. The method of claim 23 wherein said step of dumping
charge into said capacitor and resetting said integrator
comprises triggering a one shot timer, said timer having a
predetermined period, said one shot timer being connected
10 to a source of electric charge, and said triggered one
shot connects said source of electric charge to said
summing node for said period.

15 25. The method of claim 23 further comprising counting
the number of said resets of said integrator.

20 26. A method of supplying and measuring incident
radiation comprising:

supplying penetrating radiation;

striking a detection device with penetrating
radiation producing output electrical current
25 from said detection device and said output
electrical current is related to said
penetrating radiation incident on said detection
device;

30 integrating said detection device output electrical
current and producing a first voltage;

generating an integrator input current proportional
to said first voltage and connecting said
35 integrator input current to a summing node;

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integrating said integrator input current through an
integrator having an input connected to said
summing node, a capacitor connected between said
summing node and the output of said integrator,
5 and the polarity of said integrator input
current being opposite the polarity of said
capacitor at said summing node;

comparing said output from said integrator to a
10 reference voltage and dumping charge into said
capacitor when said output from said integrator
approximately equals said reference voltage,
resetting said integrator and having no latent
period during reset of said integrator.

15

27. A method of quantifying the energy incident to
detection devices in a radiography application comprising:

20 striking detection devices with penetrating radiation
producing output electrical currents from each
of said detection devices and said output
electrical currents are related to said
penetrating radiation incident on each of said
25 detection devices;

integrating said detection device output electrical
currents individually and producing individual
first voltages associated to each detection
30 device;

individually amplifying each of said first voltages
in a variable gain amplifier exclusive to each
detection device, each variable gain amplifier
35 producing an amplified voltage level and having

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a variable gain control connected to a
normalization controller;

individually generating integrator input currents,
each said integrator input current being
proportional to its associated amplified
voltage, and each said integrator input current
being exclusively connected to its associated
summing node;

integrating each of said integrator input currents
through an integrator exclusively associated to
each said summing node, each having an input
connected to each associated said summing node,
each having a capacitor connected between each
associated said summing node and the output of
said integrator, and the polarity of each said
integrator input current being opposite the
polarity of the associated said capacitor at its
associated said summing node;

individually comparing said output from each said
integrator to a reference voltage and dumping
charge individually into said capacitor when the
associated said output from said integrator
approximately equals said reference voltage,
resetting its associated said integrator and
having no latent period during reset of said
integrator.

28. The method of claim 27 wherein said step of dumping
charge into said capacitor and resetting said integrator
comprises triggering a one shot timer, said timer having a
predetermined period, said one shot timer being connected
to a source of electric charge, and said triggered one

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shot connects said source of electric charge to its associated said summing node for said period.

5 29. The method of claim 27 further comprising individually counting the number of said resets of each said integrator.

10 30. The circuit of claim 27 wherein said normalization controller measures and compares each of said variable gain amplifiers and adjusts each associated said variable gain control and normalizes said amplified voltage levels.

15 31. A method of supplying and measuring incident radiation comprising:

supplying penetrating radiation;

20 striking detection devices with penetrating radiation producing output electrical currents from each of said detection devices and said output electrical currents are related to said
25 penetrating radiation incident on each of said detection devices;

integrating said detection device output electrical currents individually and producing individual
30 first voltages associated to each detection device;

individually amplifying each of said first voltages in a variable gain amplifier exclusive to each
35 detection device, each variable gain amplifier producing an amplified voltage level and having

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a variable gain control connected to a normalization controller;

individually generating integrator input currents,
each said integrator input current being
proportional to its associated amplified voltage
and each said integrator input current being
exclusively connected to its associated summing
node;

integrating each of said integrator input currents
through an integrator exclusively associated to
each said summing node, each having an input
connected to each associated said summing node,
each having a capacitor connected between each
associated said summing node and the output of
said integrator, and the polarity of each said
integrator input current being opposite the
polarity of the associated said capacitor at its
associated said summing node;

individually comparing said output from each said
integrator to a reference voltage and dumping
charge individually into said capacitor when the
associated said output from said integrator
approximately equals said reference voltage,
resetting its associated said integrator and
having no latent period during reset of said
integrator.

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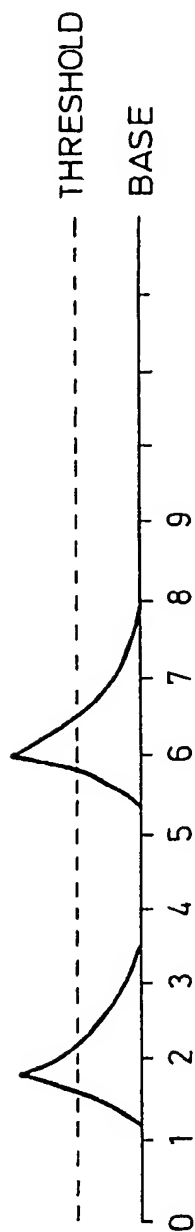


FIG. 1a

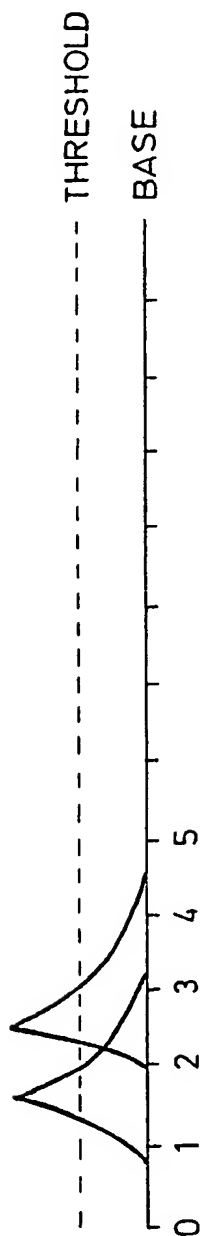


FIG. 1b

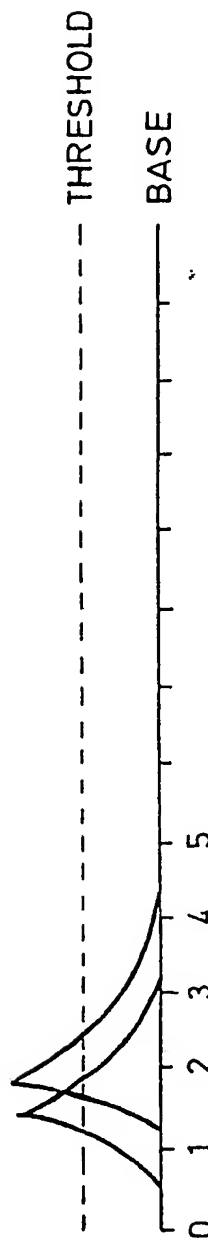


FIG. 1c

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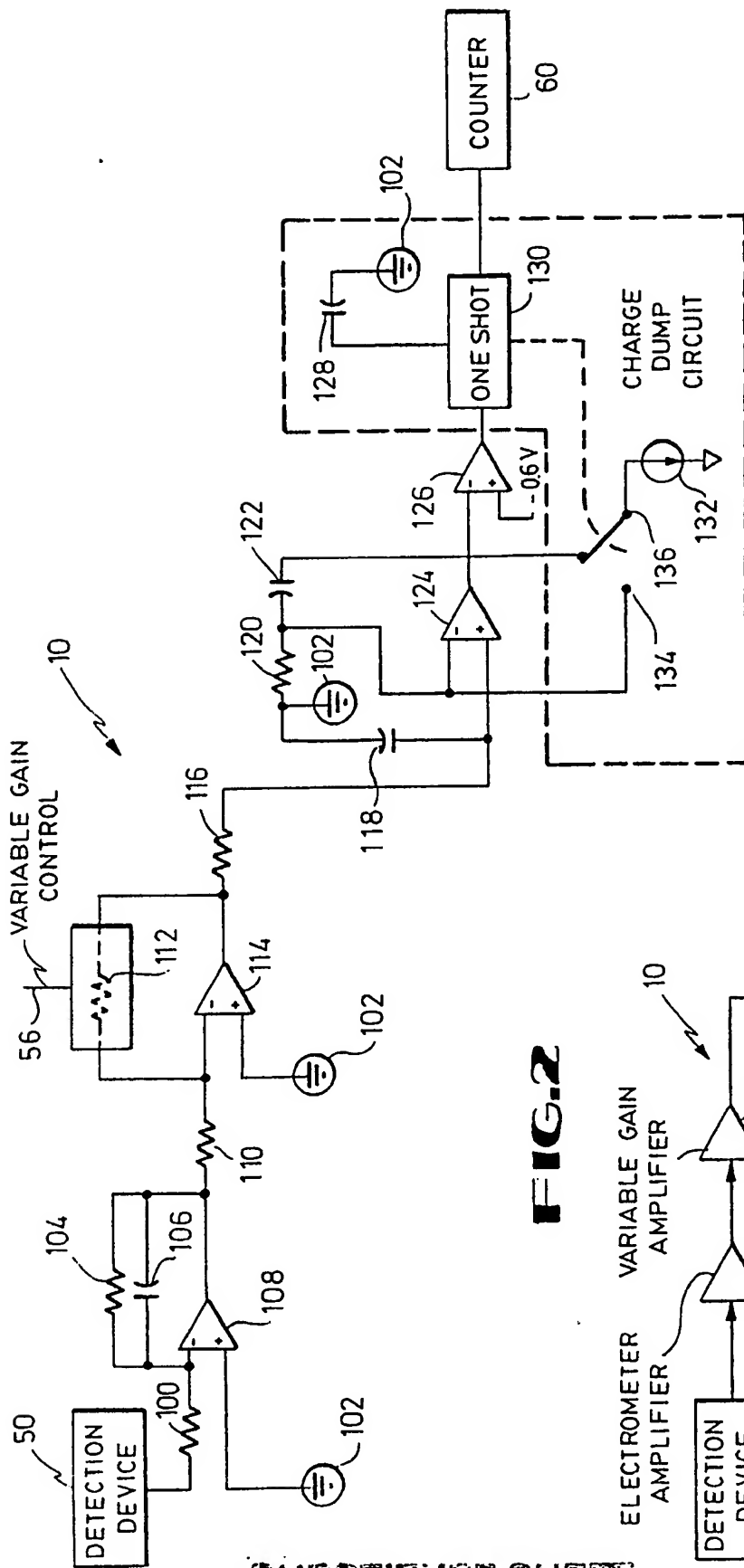


FIG. 2

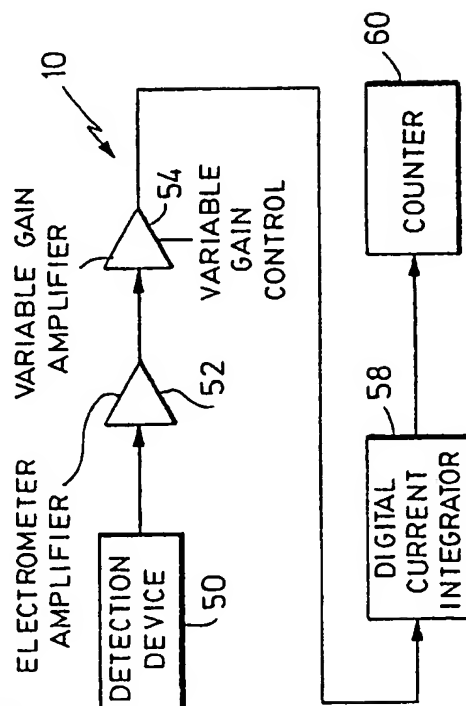


FIG. 3

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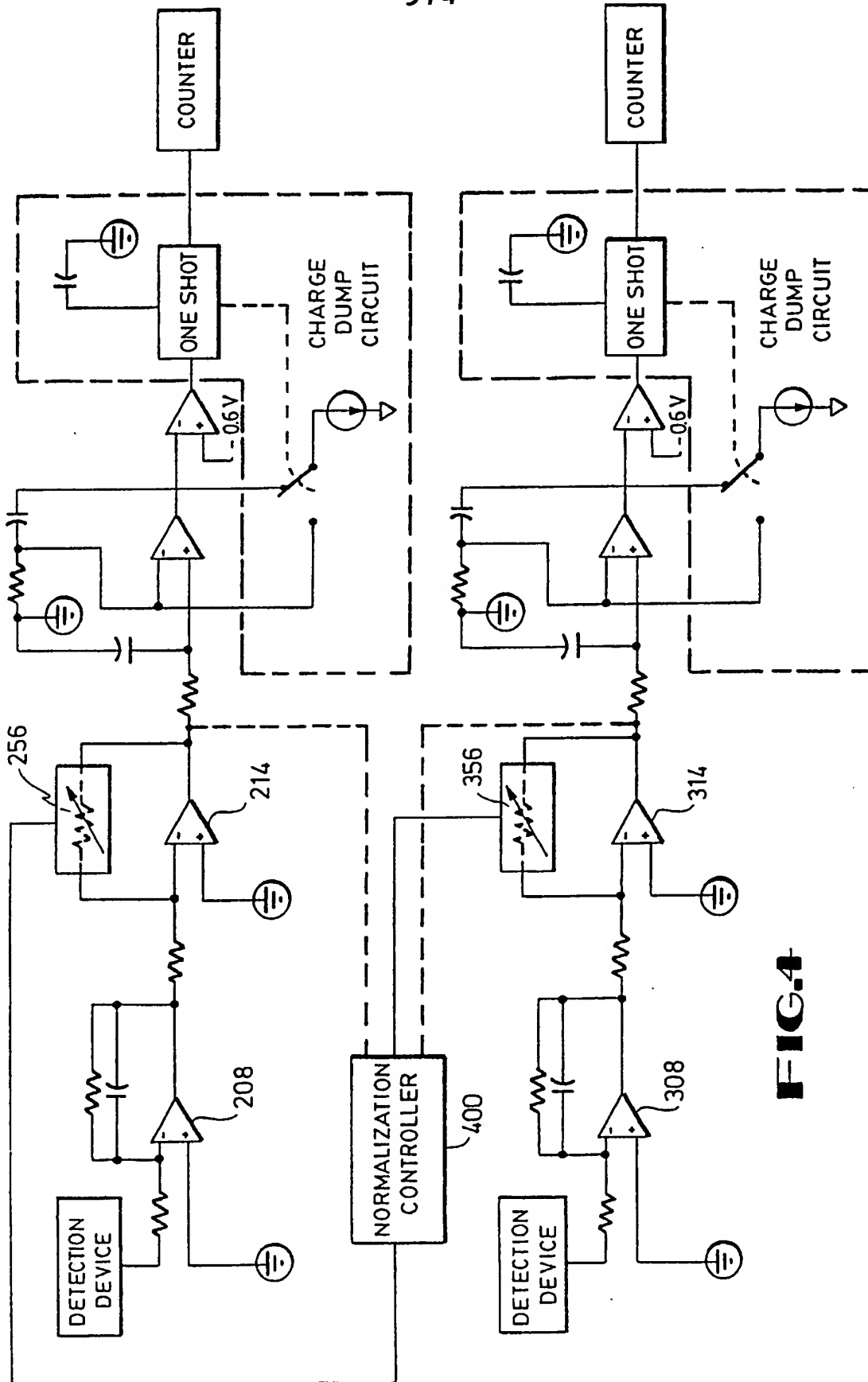
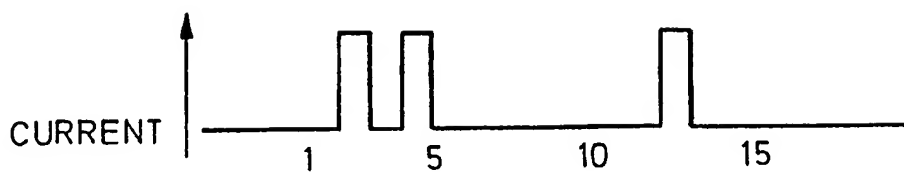
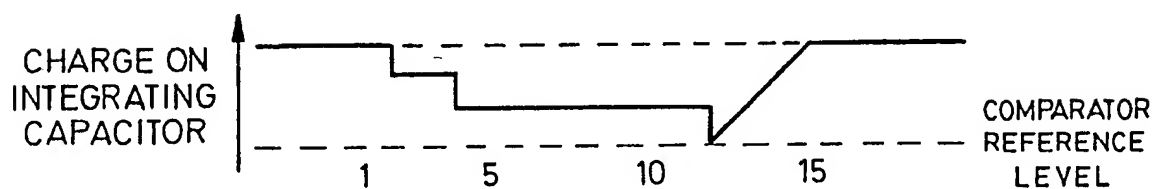
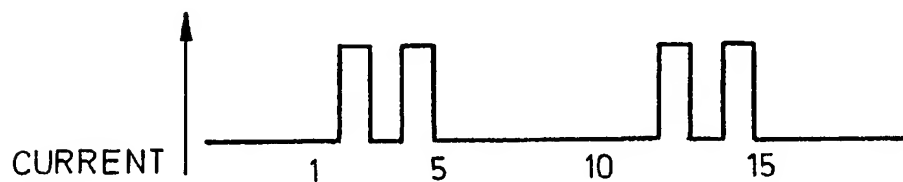
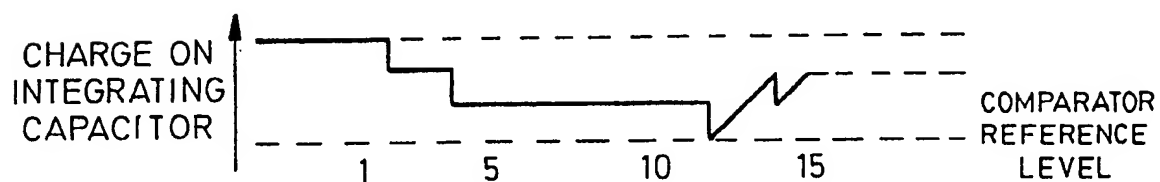


FIG. 4

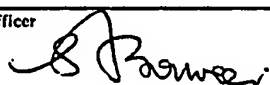
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**FIG. 5a****FIG. 5b****FIG. 5c****FIG. 5d**

INTERNATIONAL SEARCH REPORT

International Application No

PCT/US 90/02442

I. CLASSIFICATION OF SUBJECT MATTER (If several classification symbols apply, indicate all) ⁶		
According to International Patent Classification (IPC) or to both National Classification and IPC Int.Cl. 5 G01T1/17		
II. FIELDS SEARCHED		
Minimum Documentation Searched ⁷		
Classification System	Classification Symbols	
Int.Cl. 5	G01T	
Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included In the Fields Searched ⁸		
III. DOCUMENTS CONSIDERED TO BE RELEVANT⁹		
Category ¹⁰	Citation of Document, ¹¹ with indication, where appropriate, of the relevant passages ¹²	Relevant to Claim No. ¹³
A	US,A,4491733 (WASSERMAN P.D.) 01 January 1985 see abstract; claims 1-13; figures 1-3 ---	1
A	US,A,4767929 (VALENTINE K.H.) 30 August 1988 see abstract; claims 1-5; figure 1 ---	1
A	GB,A,2135451 (N.V. PHILIPS' GLOEILAMPENFABRIEKEN) 30 August 1984 see abstract; claims 1-3; figure 1 ---	1
A	NUCLEAR INSTRUMENTS AND METHODS. vol. A240, no. 1, October 1985, AMSTERDAM NL pages 130 - 134; Benulis C.A. et al.: "A Subnanosecond Time Discriminator System" see the whole document ---	1
<p>¹⁰ Special categories of cited documents:</p> <p>"A" document defining the general state of the art which is not considered to be of particular relevance</p> <p>"E" earlier document but published on or after the international filing date</p> <p>"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)</p> <p>"O" document referring to an oral disclosure, use, exhibition or other means</p> <p>"P" document published prior to the international filing date but later than the priority date claimed</p> <p>"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention</p> <p>"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step</p> <p>"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.</p> <p>"&" document member of the same patent family</p>		
IV. CERTIFICATION		
Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report	
12 SEPTEMBER 1990	01. 10. 90	
International Searching Authority	Signature of Authorized Officer	
EUROPEAN PATENT OFFICE	BAROCCI S. 	

**ANNEX TO THE INTERNATIONAL SEARCH REPORT
ON INTERNATIONAL PATENT APPLICATION NO.**

US 90/02442

SA 37429

This annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report.
The members are as contained in the European Patent Office EDP file on

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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US-A-4491733	01-01-85	None	
US-A-4767929	30-08-88	None	
GB-A-2135451	30-08-84	FR-A, B 2540995	17-08-84
		DE-A- 3403528	16-08-84
		JP-A- 59157584	06-09-84
		NL-A- 8400438	03-09-84
		US-A- 4603256	29-07-86